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Journal of Nuclear Materials 258–263 (1998) 1791–1797

journal of nuclear materials

Impact of low activation materials on fusion reactor design

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Abstract

The following impact of low activation materials to the fusion reactor design are described based on the design of five fusion power reactors with different structural material/coolant combinations. (1) Reduce the radioactive impact to the environment in case of severe accidents. (2) Reduce the radioactive impact to the environment during normal operation. (3) Reduce the decay heat during the maintenance and in case of loss of cooling accidents. (4) Reduce the gamma-ray dose during the maintenance. (5) Reduce the amount and lower the level of radioactive waste from replaced components and at the decommissioning of a fusion reactor. In order to reduce environmental impact in case of severe accidents to the level such as to enable construction of a fusion reactor near big cities, the low activation material must be of very low activity such as may only be achievable by SiC/SiC composites.

1. Introduction

With the use of low activation materials in fusion reactors, there is a possibility to totally exclude severe accident and this could allow the construction of fusion reactors near the big cities where the electric power is mostly consumed. The effect of radioactivity in different structural materials have been compared by many authors [1–8]. This paper aims to show the impact of low activation material to fusion reactor design by comparing five types of reactor design. It should be stressed that although low activation is only one of the requirements for fusion reactor blanket materials it is however the most important in achieving the safe and environmentally attractive fusion reactor.

2. Fusion power reactors considered

In fusion reactors, the activation characteristics varies greatly with the choice of the structural materials because it is generated by the interaction of 14 MeV neutrons and the structural materials. The activation level and its decay with time depends on the radionuclides generated. Five types of candidate structural materials, namely, SS316, low activation ferritic steel F82H [9], TiAl intermetallic compound, V-Alloy (V-4Cr-4Ti-0.1Si) prepared in Tohoku University [10] and SiC/SiC composite with impurities prepared in National Research Institute of Metals [11] have been selected for comparison. The standard case reactor concept is the Steady State Tokamak Reactor (SSTR) [12] which uses F82H and is cooled by pressurized water. In the second concept named SSTR-316, SS-316 is used in place of F82H. The third is the SSTR-2 concept [13] using TiAl intermetallic compound structural cooled by helium gas. The fourth concept is the ARIES-RS [14] using V-alloy and liquid lithium cooling and the DREAM Reactor [15] which uses SiC/SiC composite [11] and helium cooling. The elemental compositions of these five materials are shown in Table 1.

3. Activation calculations

The activation level, decay heat, volume of radioactive waste (radwaste) generated during operation and at decommissioning, are evaluated for fusion power reactors having five types of structural materials.

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0022-3115/98/$19.00
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Table 1
Elemental composition of the candidate structural materials (wt%)

Element	Material type				
	F82H (SSTR)	SS-316 (SSTR316)	TiAl (SSTR2)	V-alloy (ARIES)	SiC/SiC (DREAM)
B	3.41×10^{-3}	–	–	–	–
C	9.30×10^{-2}	6.92×10^{-3}	–	–	2.99×10^{-1}
N	1.90×10^{-3}	9.88×10^{-3}	–	–	1.00×10^{-2}
O	–	–	–	–	3.80×10^{4}
Na	–	–	–	–	1.70×10^{-4}
Al	1.00×10^{-2}	–	$3.60 \times 10^{+1}$	1.70×10^{-3}	5.60×10^{-5}
Si	8.98×10^{-2}	$1.62 \times 10^{+0}$	–	1.88×0^{-1}	$6.97 \times 10^{+1}$
P	5.00×10^{-3}	2.57×10^{-2}	–	–	–
S	9.99×10^{-4}	1.19×10^{-2}	–	–	–
Cl	–	–	–	–	2.00×10^{-2}
K	–	–	–	–	8.20×10^{-5}
Ti	5.00×10^{-5}	–	$6.40 \times 10^{+1}$	$4.00 \times 10^{+0}$	1.90×10^{-4}
V	1.80×10^{-1}	–	–	$9.18 \times 10^{+1}$	3.00×10^{-5}
Cr	$7.66 \times 10^{+0}$	$1.64 \times 10^{+1}$	–	$4.00 \times 10^{+0}$	2.10×10^{-4}
Mn	4.91×10^{-1}	$1.88 \times 10^{+0}$	–	–	8.00×10^{-5}
Fe	$8.94 \times 10^{+1}$	$6.47 \times 10^{+1}$	–	1.20×10^{-2}	4.50×10^{-4}
Ni	1.00×10^{-2}	$1.27 \times 10^{+1}$	–	–	8.00×10^{-5}
Co	5.01×10^{-3}	2.77×10^{-1}	–	–	–
Cu	–	–	–	–	2.10×10^{-4}
Zn	–	–	–	–	3.70×10^{-5}
Zr	–	–	–	–	1.00×10^{-4}
Nb	7.00×10^{-5}	–	–	1.50×10^{-3}	–
Mo	1.00×10^{-2}	$2.26 \times 10^{+0}$	–	4.00×10^{-4}	2.20×10^{-5}
Sc	–	–	–	–	2.10×10^{-7}
Ba	–	–	–	–	4.00×10^{-5}
Hf	–	–	–	–	1.60×10^{-5}
Ta	3.80×10^{-2}	–	–	–	–
W	$1.98 \times 10^{+0}$	–	–	–	1.00×10^{-5}
Au	–	–	–	–	1.00×10^{-8}
Pt	–	–	–	–	2.00×10^{-4}

It is assumed that the replaceable components facing the plasma with thickness of about 20 cm will be irradiated at a neutron wall load of 5 MW/m^2 for two full power years and replaced every 2 yr. The structures behind the replaceable components receive neutron wall load less than 0.5 MW/m^2 during the lifetime of 20 full power years and then are decommissioned. A cooling period of 50 years is assumed before disposal. For both types of components the maximum fluence reaches up to 10 MW a/m^2. In such a case, it is necessary to consider the reaction of neutron with the product nuclides from previous nuclear reactions, namely, multi-step nuclear reactions. The FISPACT-3 code [16] and EAF-3 activation cross-section library [17] which are capable of treating multi-step reactions, are used for the activation calculations.

The activation of fusion reactor blanket, shield and magnet were calculated using 1D models. The neutron fluxes were calculated with the ANISN code [18] and a 175 group cross-section set derived from JENDL-3.1 evaluated nuclear data. The calculated neutron fluxes were used in the FISPACT activation calculation.

4. Radioactive material release

The radioactive material release during the normal operation are considered to be mainly in the form of dust and corrosion products in the coolant of the primary heat transfer system. The dust is produced by the erosion of first wall or divertor plate through sputtering and evaporation by the plasma disruptions. The dust could come out during the maintenance operations. Corrosion products in the coolant could be released with the coolant leakage from the primary heat transfer system. The use of low activation materials will lower the activation levels in the structural material. However, the fraction to be released will depend on the fraction of materials mobilized and to be transported out of the confinement.

The radioactive material release during accidents depends on the accident scenario, mobilization and transport mechanisms.

The low inventory of activation products could ease the design measures against mobilization and transport outside the confinement. Also the low activation concept should reduce the release of radioactivity during the normal operation to very low level to enhance the public acceptability of the fusion reactor. Fig. 1 shows the time evolution of induced activity per ton of the five materials in the first wall irradiated for 2 yr at 5 MW/m^2. It can be observed that in the short term for about one year after the shutdown of the reactor, the induced activity of SiC/SiC composites is lower than the other materials by orders of magnitude. V-alloy is more than one order of magnitude lower than SS-316 and F82H.

Activated material release limit based on 10 mSv early dose at a 1 km site boundary under conservative weather conditions has been evaluated by Petti et al. [8] It is about 140 g for SS-316, 370 g for a low activation ferritic steel, 510 g for V-alloy. Although not evaluated here SiC/SiC could be around 50 kg which is a highly unlikely amount to be released even in severe accidents. In order to reduce environmental impact in case of severe accidents to the level such as to enable construction near big cities, the low activation material must be of very low activity such as only achievable by SiC/SiC composite.

5. Decay heat

Decay heat from the activated materials in a fusion reactor necessitates cooling during the shutdown of the plasma and also during the maintenance operations. In addition to the usual cooling system used to remove the heat during plasma operation, extra means of cooling may become necessary for cooling during the maintenance after the cooling pipe is disconnected for replacement.

In case of loss of cooling accident, an emergency cooling system may be needed to remove the decay heat. Should decay heat removal fail, temperature of the activated components could rise to high enough to cause melting to loose the integrity of the confinement boundary or to increase the possibility of chemical reactions in case of reactive gas ingress to the hot components.

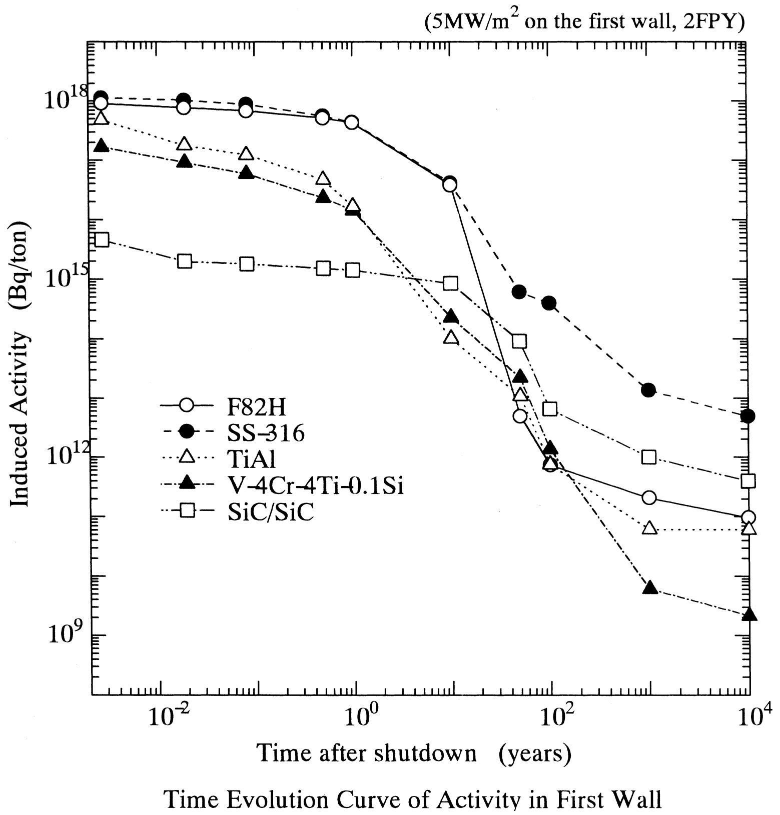

Fig. 1. Time evolution of induced activity per ton of the five materials in the first wall irradiated for 2 yr at 5 MW/m^2.

As for the long term decay heat relevant to radioactive waste (radwaste) management, lower decay heat will enable the disposal without the interim storage the cost of which is non-trivial in our previous study [19].

Low activation materials with low decay heat impact the design by simplifying the cooling system and/or by decreasing the requirement for the safety system against accidents caused by the decay heat.

Fig. 2 shows the time evolution of decay heat per m^3 of the five materials in the first wall. Here again, the decay heat of SiC/SiC is lower than the other materials by up to three orders of magnitude for up to 10 yr. This could mean no need for active cooling during maintenance or radwaste and no need for emergency cooling in case of accidents.

6. Gamma-dose during maintenance

Gamma-ray dose from activated materials will preclude personnel access to the highly activated area of the fusion reactor plant. Remote maintenance will be employed for the highly activated components in the vacuum vessel. For in-vessel maintenance, the lifetime of remote maintenance tools must be long enough to conduct replacement of damaged parts with the new one. To withstand about 300 h in the irradiation environment of 0.3 MGy/h in the in-vessel for ITER, various remote maintenance components are being developed [20]. For components with lower irradiation such as pumps of a primary cooling system where activated corrosion products may circulate, hands on maintenance is desirable. If the radiation level is high, such components may also need to be remotely handled.

Reduction of gamma-ray dose during the maintenance of a fusion reactor eases the requirement of radiation hardening of the remote maintenance components. Low contact dose could reduce the worker dose. Furthermore increased personnel access could result in higher reliability/availability of the fusion plant.

Fig. 3 shows the time evolution of contact dose rate for the five materials in the first wall. Here again, the contact dose for the SiC/SiC is lower than the others by up to 4–5 orders of magnitude in the short term up to 1 yr after the shutdown.

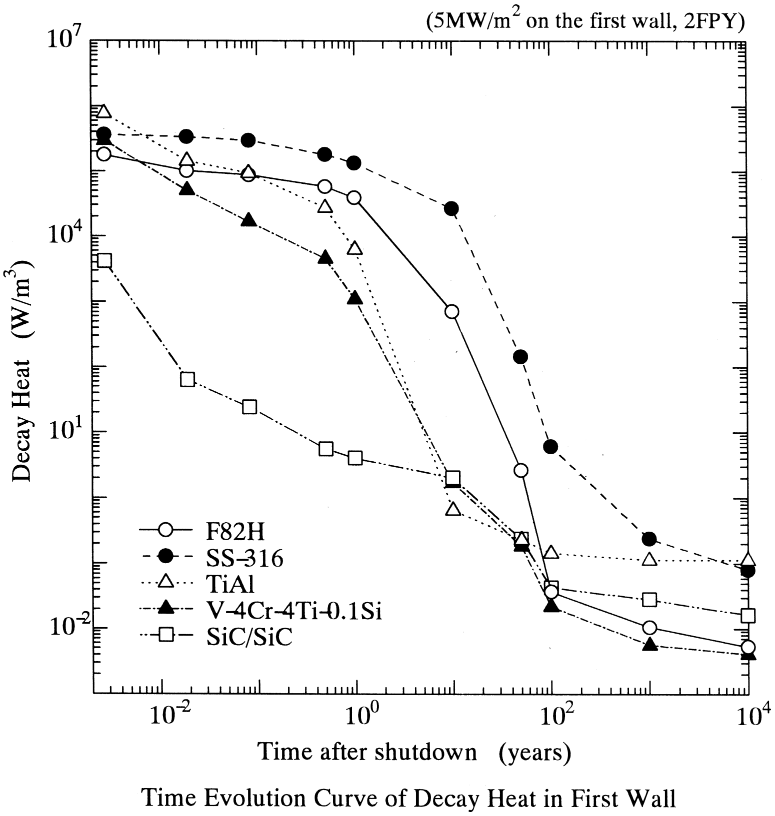

Fig. 2. Time evolution of decay heat per m^3 of the five materials in the first wall irradiated for 2 yr at 5 MW/m^2.

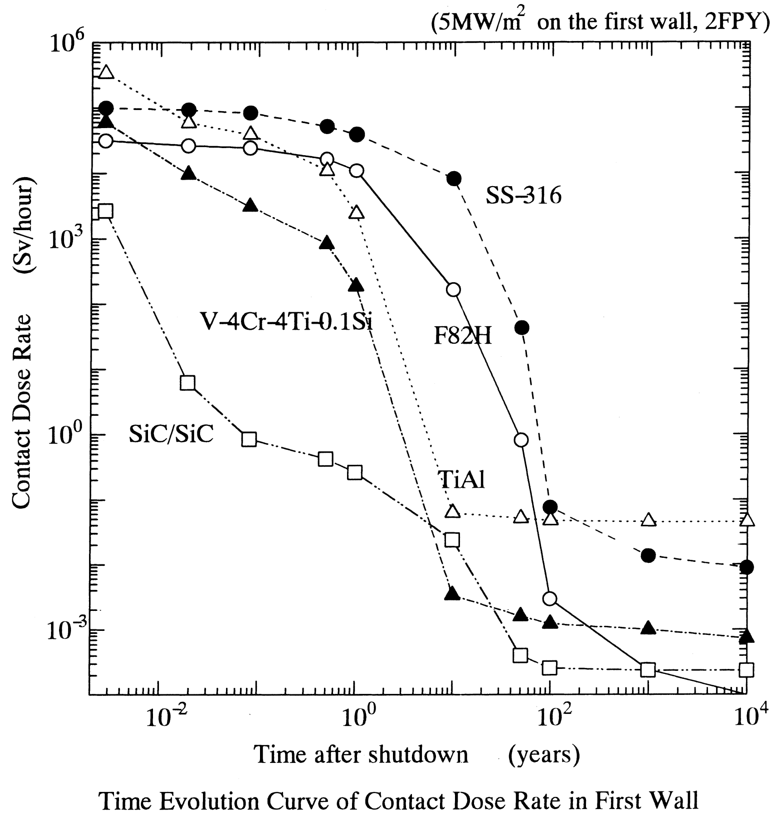

Fig. 3. Time evolution of contact dose rate of the five materials in the first wall irradiated for 2 yr at 5 MW/m^2.

7. Radioactive waste disposal

In Japan, fission waste having any single radionuclide exceeding the limiting concentration value determined by Nuclear Safety Commission will not qualify as low level waste (LLW), which could be disposed of by shallow land burial [21]. The limiting concentrations values of radionuclides causing a 10 μSv/yr individual dose from shallow land disposal are derived and shown in Table 2. Most of the radionuclides are characteristic to fusion and such values have been newly derived based on the 100 μSv/yr individual dose using the method of Nuclear Safety Commission. For three nuclides, ^{14}C, ^{60}Co and ^{63}Ni, the values used for fission waste in Japan are also shown in Table 2. The similarity of the derived values and the values used for fission waste demonstrate the validity of the present derivation. For these three nuclides, the values already authorized are used as the limiting concentration for assigning the fusion waste as LLW.

The radwaste generated by the five fusion power reactors were classified into LLW and medium level waste, MLW which is defined here as those not qualifying for LLW because any one of the radionuclides in Table 2 exceeds the limiting concentration value. Results of the classification of radwaste by volume from five fusion reactors are shown in Table 3. It shows that MLW fraction is only 10% for SSTR, 21% for SSTR2 and between 37% and 54% for other reactors. The fraction for ARIES-RS is large but the amount of MLW is not much because of the compactness of the reactor core. It should also be noted that the fraction of MLW may be reduced if Nb impurity content in V-alloy could be reduced. Although it is not being carried out as yet, MLW of a fusion reactor could be disposed of by geological disposal the cost of which is considered to be not much different from shallow land disposal. The cost of interim storage for 30 yr before geological disposal which is quite expensive in case of fission waste could be deleted for fusion reactor with low decay heat.

8. Summary

This paper is summarized as follows

1. Low activation is only one of the requirements for fusion reactor blanket material but it is the most important to achieve the safe and environmentally attractive fusion reactor.

Table 2
Limit of disposal of low-level waste by shallow land disposal

Radio-nuclide	Concentrations derived on basis of 10 μSv/yr individual dose (Bq/g)			Limiting concentrations (Bq/g)	
	Skyshine	Groundwater migration	Future use	Derived value [a]	Regulation in Japan [b]
^{3}H	–	2.0975×10^{9}	* [c]	1.85×10^{10}	–
^{10}Be	–	2.5102×10^{7}	1.2227×10^{4}	1.11×10^{5}	–
^{14}C	–	5.6967×10^{6}	1.8645×10^{3}	1.85×10^{4}	3.70×10^{4}
^{26}Al	6.6815×10^{5}	7.0922×10^{4}	8.4250×10^{0}	7.40×10^{1}	–
^{36}Cl	–	6.2521×10^{4}	1.8696×10^{4}	1.85×10^{5}	–
^{60}Co	1.2651×10^{6}	*	*	1.11×10^{7}	1.11×10^{7}
^{59}Ni	–	5.0588×10^{11}	6.2616×10^{3}	5.55×10^{4}	–
^{63}Ni	–	*	1.6397×10^{5}	1.48×10^{6}	1.11×10^{6}
^{91}Nb	–	*	1.4248×10^{4}	1.11×10^{5}	–
^{94}Nb	7.3530×10^{6}	6.2195×10^{8}	2.4828×10^{1}	2.22×10^{2}	–
^{93}Mo	–	1.0112×10^{7}	2.6139×10^{2}	2.22×10^{3}	–
^{186m}Re	–	6.4337×10^{5}	7.2235×10^{3}	7.40×10^{4}	–
^{192n}Ir	–	*	7.3226×10^{0}	7.40×10^{1}	–
^{193}Pt	–	*	2.1498×10^{5}	1.85×10^{6}	–

[a] These values are derived on basis of 100 μSv/yr individual dose (risk of 10^{-6}/yr) using the method of Nuclear Safety Commission. Note that the values are converted to the nearest multiples of 37 or conversion to Ci unit.
[b] Nuclear Safety Commission derives these values for disposal of low-level waste from fission reactors using the method described in IAEA-TECDOC-401.
[c] An asterisk indicates a value greater than 1.0×10^{15}.

Table 3
Classification of fusion radwaste (radwaste amount in ton/1GWe)

Reactor	LLW	MLW
SSTR	24 700 (90%)	2900 (10%)
SSTR316	17 400 (63%)	10 400 (37%)
SSTR2	28 200 (79%)	6000 (21%)
ARIES-RS	6000 (46%)	7000 (54%)
DREAM	13 500 (57%)	10 200 (43%)

2. Radioactive waste disposal is only one aspect of the impact of low activation material on fusion reactor design.
3. From the view point of fusion reactor designer, SiC/SiC composites offer the possibility of siting fusion reactor near big cities and its development is highly desired.

Acknowledgements

Authors thank Mr. K. Obara of JAERI-Naka for the irradiation data of remote maintenance equipment and Dr. T. Nagashima and Dr. M. Ohta of JAERI-Naka for the support of this work.

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